Physical volcanology of lava flows on Surtsey, Iceland: A preliminary report

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ABSTRACT

The Surtsey volcano is situated off the central-south coast of Iceland and was formed by a prolonged submarine volcanic eruption between November 1963 and June 1967. The prominent features on Surtsey are two abutting ~140 m high tuff cones and small pahoehoe lava flow field that caps the southern half of the island. Although best known for its surtseyan explosive activity, the eruption featured two distinct subaerial effusive phases that produced two small pahoehoe lava shields. The first effusive phase lasted for 13.5 months and produced a 100 m high lava shield with a total volume of 0.25–0.30 km^3. The second effusive phase formed a 70 m high lava shield (volume ~0.1 km^3) and lasted for 9.5 months. The observations presented here show that the Surtsey lava shields consist of two principal structural units, the lava cone and the outer lava apron. The lava cones formed during the early stages of each effusive phase by surface flows that emanated from lava ponds in the summit lava craters and produced shelly pahoehoe and sheet flows. The lava apron is a later stage construction, formed when the level of the lava ponds had dropped well below the rims of the summit lava craters. At this stage the flow of lava to the active flow fronts was essentially confined to internal pathways such as lava tubes. As the lava emerged from the tubes it spread to form either a series of small budding lava lobes or broad but thin sheet lobes.

INTRODUCTION

Surtsey island is a small (~2.5 km^2) volcanic island situated about 33 km off the central-south coast of Iceland that belongs to the mildly alkalic Vestmannaeyjar volcanic system which is located on the seaward extension of the Eastern Volcanic Zone (Jakobsson 1979). The prominent features on Surtsey are two abutting ~140 m high tuff cones and a small pahoehoe lava flow field that caps the southern half of the island (Fig. 1). The island is the subaerial part of the larger Surtsey volcano, a 6 km long east-northeast (E65°N) trending submarine ridge that rises from a depth of 125 m and covers ~14 km^2 (Fig. 2). The volcano was produced by a prolonged eruption that began in early November 1963 and lasted until June 1967. Although best known for its explosive ('surtseyan'; Walker 1973) activity, the eruption featured several distinct eruptive phases including two prolonged subaerial effusive phases that produced two small partly overlapping pahoehoe lava shields and five much smaller a'a lava flows (Table 1). Effusive phase I lasted for 13.5 months (4 April 1964 - 17 May 1965) and produced a 100 m high lava shield with a subaerial coverage of 1.53 km^2. The total volume of lava produced by this phase was about 0.25 -0.30 km^3 when the volume of the submarine foundation is included. Effusive phase II lasted for 9.5 months (19 August 1966 - 5 June 1967) and produced an ~70 m high lava shield that above sea level covered ~1 km^2, of which 0.5 km^2 was a new addition to the island. The total volume of lava produced by

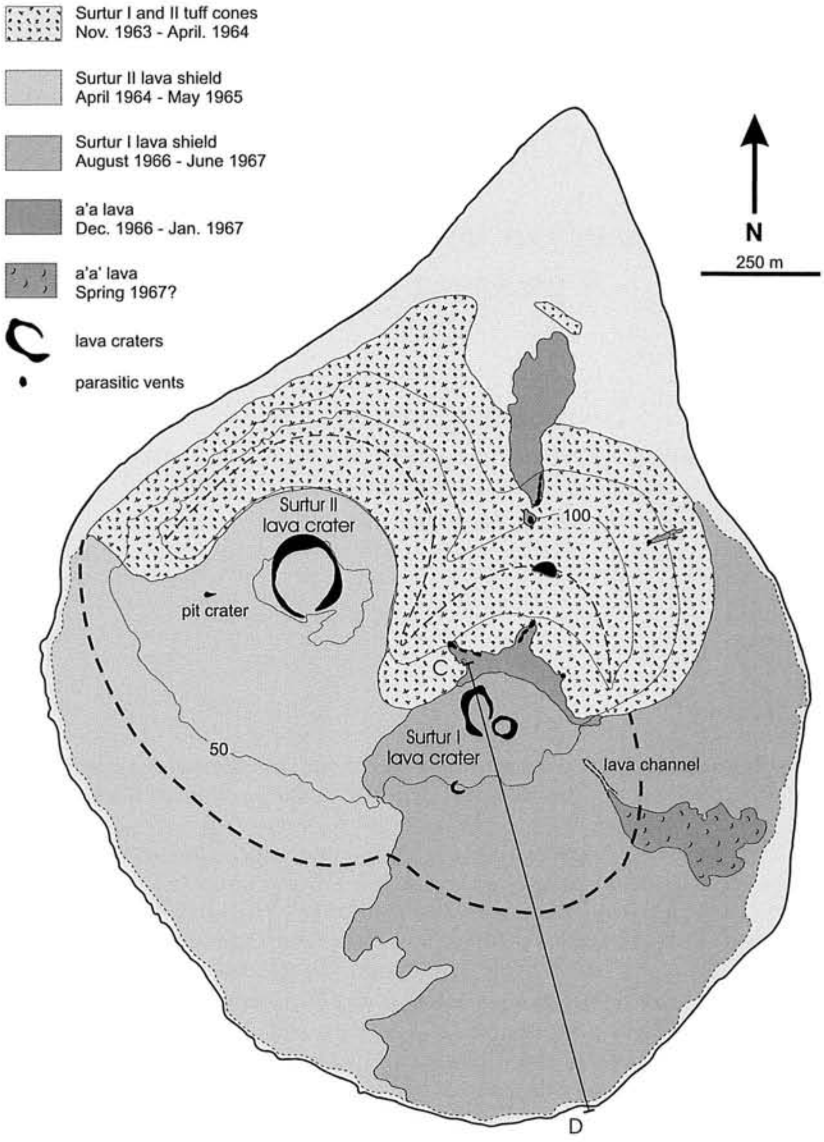

Figure 1. Simplified geological map of Surtsey showing the outlines of the island as they were in 1975. Heavy broken line indicates the boundary between the lava cones and the lava aprons, which are the main structural units of the lava shields. Solid line C-D indicates location of the cross section shown in Figure 3. See key for other explanations. Modified from Jakobsson and Moore (1982).

the Surtur I lava craters was ~0.1 km³. The total volume of tephra and lava produced by the Surtsey eruption amounts to 1.0 - 1.2 km³, of which ~30% (0.3 - 0.4 km³) were erupted as lava. The original volume of lava above sea level did not exceed 0.1 km³ and most likely was of the order of 0.07 km³.

Here I report on miscellaneous volcanological observations made on the Surtsey lavas during a weeklong visit to the island in the summer of 1991. The implications of these observations for the characteristic lava emplacement mechanisms at Surtsey are briefly discussed and will be reported in more detail elsewhere. The terminology used here to describe lava flows and structures is adapted from Macdonald (1967), Swanson (1973), Walker (1991), Self *et al.* (1997), and Thordarson & Self (1998). However, it should be noted that here the terms *sheet flow* and *sheet lobe* are used to describe two distinct lava types. Sheet flow is used here to describe broad and sheet-like surface flows, which originated in the lava craters as fountain-fed or overbank flows similar to those described by Swanson (1973). On the other hand, the term sheet lobe is used to describe tube-fed inflated pahoehoe flows of sheet-like geometry (e.g., Self *et al.*, 1998).

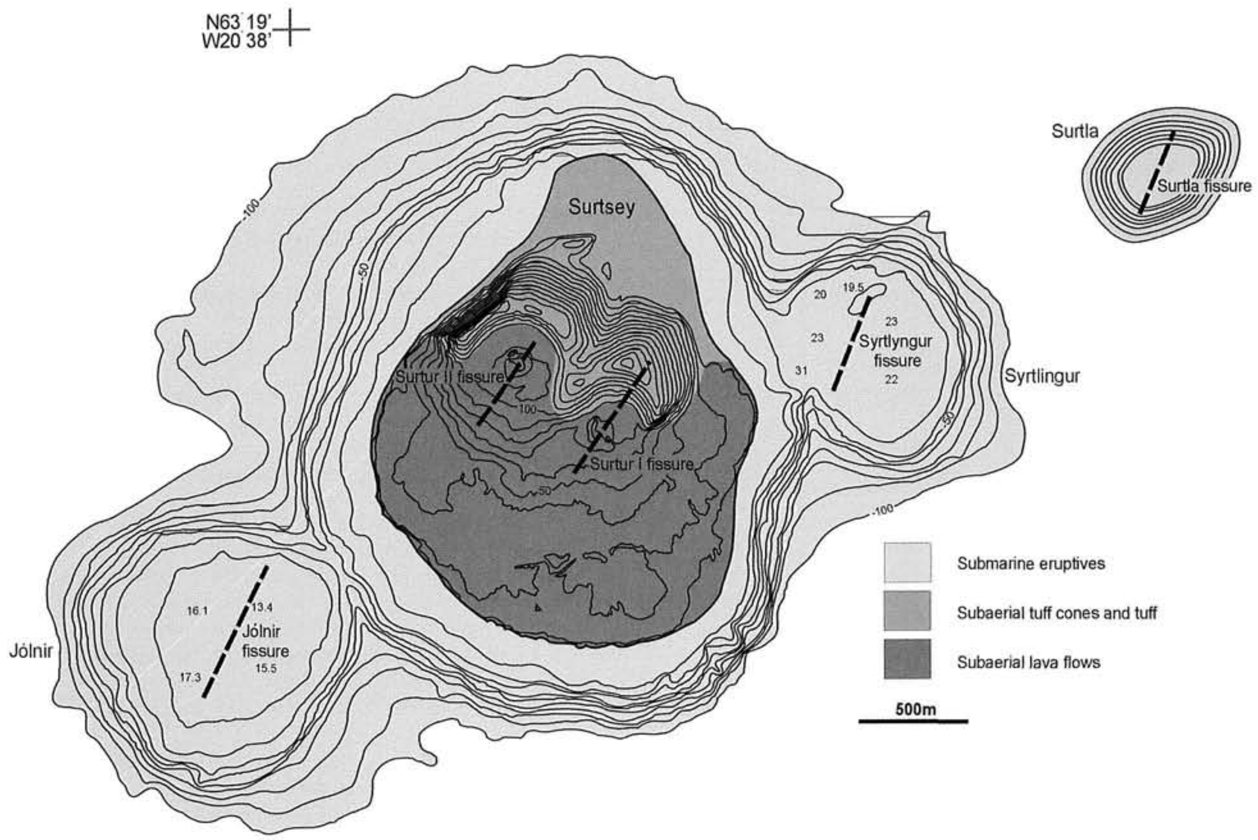

Figure 2. Map of the Surtsey volcano showing the submarine (July, 1967) and subaerial (July 1968) topography. Also shown are the volcanic fissures, submarine and subaerial cones and the lava flow field on Surtsey.

THE SURTSEY LAVA FLOW FIELD

Geometry and general structure

As pointed out in previous studies (e.g. Einarsson 1965, Thórarinsson 1966, 1968, Kjartansson 1966a 1966b, 1967, Jakobsson & Moore 1982), the geometry and profile of the subaerial parts of the Surtur I and II lavas are identical to that of other lava shields in Iceland (Fig. 3). Consequently, the Surtsey lava flow field can be viewed as consisting of two small overlapping half-shields. The shields are capped by 70 m to 130 m wide lava craters encircled by 48 m high spatter rings. The lava craters are nested in the earlier formed Surtur I and II tuff cone craters (Fig. 1). The spatter ramparts, standing 10 to 20 m above the current crater floors, consist of red to black spatter bombs intercalated with centimetre-thick layers of lava. Individual spatter bombs are 150-300 cm long and 20-30 cm thick. The lava craters are flanked by a relatively steeply sloping lava field, which forms the most elevated part of the shields and referred to as the "lava cone". The Surtur I lava cone has an average slope of about 6.5° (range 6-7°), whereas the slopes of Surtur II lava cone are somewhat steeper, or 9.5° on average (range 8-11°). The outer limits of the lava cones are marked by sharp change in surface slope, which occurs at a distance between 350 m and 450 m from the lava craters (Fig. 1). Beyond the lava cones the Surtsey shields consist of broad and gently sloping (average 2.5°; range 0.5-4.5°) lava field, which formed a 400-500 m wide "lava apron" that originally bordered the southern half of the island. Large parts of the lava apron have been removed by erosion, especially on the western side of the island (Fig. 4).

A small pit crater is on the Surtur II lava cone (Figs 1 and 4). Rim to rim distance of the pit crater ranges from 14 m to 27 m, and its depth extends to 21 m. It occurs above a large lava tube (≤15 m wide) that lies from the Surtur II lava crater towards the western coast of Surtsey (Hróarsson 1990). Aerial photographs show that it was formed during the eruption sometime

Table 1. Main eruption episodes identified during the Surtsey eruption. Data from Thórarinsson (1965, 1966, 1967a, 1967b, 1968) and Jakobsson and Moore (1982).

	Eruption phase and type of activity	Eruption site	Date	Events
1	Submarine activity early 11.63-14.11.63	Surtur I fissure	early.11.63	Start of eruption on sea floor
2	Subaerial explosive activity 14.11.63-31.01.64	Surtur I and Surtla	14.11.63	Visible explosive hydromagmatic eruption on Surtur I fissure
			15.11.63	Appearance of Surtsey island
			28.11.63	Submarine activity on Surtla fissure first noticed
			6.01.64	Submarine activity ceased on Surtla fissure
			31.01.64	Explosive hydromagmatic eruption ceased at Surtur I vent
3	Subaerial explosive activity 2.02.64-4.04.64	Surtur II	1.02.64	Explosive hydromagmatic eruption began at Surtur II fissure
			1-8.02.64	Concurrent hydromagmatic eruption and hawaiian fountaining at two vents on Surtur II fissure
			9.02.64	Change to purely hydromagmatic eruption at Surtur II vents
			1.03.64	Northern lagoon on Surtsey formed
4	Subaerial effusive activity 4.04.64-17.05.65	Surtur II	4.04.64	Transformation from explosive hydromagmatic eruption to effusive lava eruption. ~120m wide lava pond forms in Surtur II crater
			4-29.04.64	Effusive activity dominated by surface flows produced by overspills from the lava pond or directly fed by lava fountains
			29.04.64	Emission of surface flows stops at Surtur II crater; lava pond remains active but its level subsided well below the crater rims
			0506.64	Tube-fed lava from Surtur II crater extruded on seafloor southwest of Surtsey
			9.07.64	Emission of surface flows resumes at Surtur II lava crater
			07-08.64	Gradual transition from surface flows to channel- and tube-fed flows: Surface flows become more and more intermittent and transport of lava from vent increasingly confined to lava channels and tubes
			mid 08.64	Lava transport almost exclusively confined to lava tubes, although featuring short periods of surface flow activity.
			17.05.65	Eruption and lava effusion ceased at Surtur II lava crater
5	Submarine activity 11.05.65-17.10.65	Syrtlingur	11.05.65	Beginning (?) of submarine activity at Syrtlingur eruption site
			22.05.65	Visible explosive hydromagmatic eruption in Syrtlingur fissure
			28.05.65	First appearance of Syrtlingur island
			17.10.65	Eruption ceased at Syrtlingur fissure
			24.10.65	Syrtlingur island completely washed away
6	Submarine activity late 10.65-24.08.66	Jólnir	end 10.65	Beginning (?) of submarine activity at Jólnir fissure
			26.12.65	Visible explosive hydromagmatic activity on Jólnir fissure
			28.12.65	First appearance of Jólnir island
			10.08.66	Eruption ceased at Jólnir fissure
			31.10.66	Jólnir island completely washed away
7	Subaerial effusive activity 19.08.66-5.06.67	Surtur I and parasitic vents	19.08.66	Resumed effusive activity on Surtsey by eruption on a short fissure in the Surtur I tuff cone crater: Lava emission principally via surface flows
			end 08.66	Activity centred on northernmost vent on the fissure, which became the Surtur I lava crater that contained a small lava pond
			08-11.66	Initially effusive activity dominated by surface flows produced by overspills from the lava pond or directly fed by lava fountains, followed by gradual transition from surface flows to channel- and tube-fed flows
			1.12.66	Lava transport almost exclusively confined to lava tubes, although with short periods of surface flow activity.
			12-17.12.66	Effusive eruption on a vent on inner northwest wall of Surtur I tuff cone and produced a small a'a lava flow
			14.01.67	Effusive eruption on vents on outer north slopes of Surtur I tuff cone that produced a small a'a lava flow, which flowed into the lagoon
			18.01.67	Effusive eruption on a vent on inner north wall of Surtur I tuff cone, produced a small a'a lava flow that flowed south past the drill hole
			2.01.67	Effusive eruption on a vent on outer northeast slopes of Surtur I tuff cone that produced a tiny a'a lava flow
			27.01.67	Two ring faults formed on inner east wall of Surtur I tuff cone; a vent on the lower erupted a tiny a'a lava flow
			5.06.67	Eruption and effusion of lava ceased at the Surtur I lava crater

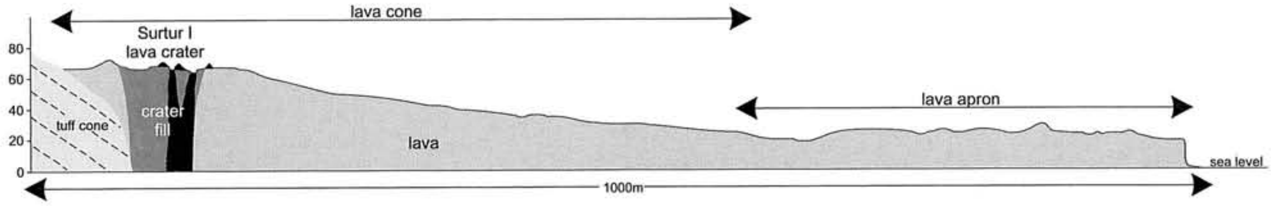

Figure 3. Profile illustrating the geometry of the Surtur I lava shield in cross section. The profile is constructed from topographic map by Norrman (1978). The extent of the lava cone and the lava apron is indicated. Location of the profile is shown on Fig. 1.

between June 1964 and October 1966, presumably by piecemeal collapse of the tube roof and overlying lavas into a partly filled and/or hollow tube.

At the end of the eruption the Surtsey lava flow field terminated at the shoreline in 3-20 m high cliffs, which due to continued marine erosion now reach heights of ~50 m on the western side of the island. These cliffs provide excellent outcrops, revealing the internal structure of the lava shields. In general they show that the shields are built of multiple lava flows of variable thickness and lateral extension. The most conspicuous units are a meter to a few meters thick and several tens to hundreds meters wide (or long) sheet-like lava bodies that most commonly are of the sheet lobe variety and to lesser extent of the sheet flow type.

The lava shields rest on ~130 m thick submarine foundation, assumed to be a foreset-bedded lava delta constructed by submarine lava effusion and disintegration of the subaerial lava flows by wave erosion and/or quenched fragmentation of lava as it entered the sea (Einarsson 1965, Thórarinsson 1966, 1968, Kjartansson 1966a, 1966b, 1967, Jakobsson & Moore 1982).

Lava surface morphology

The following descriptions of surface morphologies are based on reconnaissance on-site examination that only cover the lava cones and the Surtur I lava apron because the rest of the flow field was removed by erosion (Fig. 4). Information on diagnostic surface structures within the parts of the flow field that have been removed by erosion was obtained from analysis of aerial photographs taken by the National Land Survey of Iceland in July 1967.

In the proximity (<100 m distance) of the lava craters the surface of the steeper (6°-11°) lava cones are largely covered by ≤2 m thick lava consisting of numerous small, often budding pahoehoe lobes. Typically the lobes have very thin crusts (1-5 cm thick) and hollow interiors, which are either large gas-blisters formed by exsolving gases or small lava tubes formed as the lava was draining of the molten interior. The appearance of this lava strongly resembles the cavernous lava type called shelly pahoehoe described by Swanson (1973) from the summit region of the 1969-1973 Mauna Ulu lava shield at Kilauea in Hawaii. Patches of slabby pahoehoe also occur in this area and in places larger, smooth- or ropy-surfaced pahoehoe lobes outcrop between the smaller lobes. These lavas resemble those exposed in the walls of the pit crater, which consist of a few 1-2 m thick and poorly vesicular sheet flows that are either capped by smooth pahoehoe or cavernous slabby pahoehoe flow surfaces (Fig. 5a). On-site observations during the Surtsey eruption show that slabby pahoehoe or clinkery a'a-type surfaces were commonly formed on the rapidly advancing sheet-like surface flows, although such flows also featured smooth and ropy pahoehoe surface morphologies (Einarsson 1965, Thórarinsson 1967b).

On the outer slopes of the lava cones at 100-300 m distance from the lava craters the surface lava type is typically slabby pahoehoe, which is distinguished by its mishmash of crustal fragments that often are piled up in untidy heaps as high as 1 m (Fig. 5b). Small lava channels flanked by levees and copious subsidiary overflows are common in this sector of the lava field. Some channels are partly crusted over and downslope they transform into tumuli ridges.

The more gently sloping lava apron has a hummocky surface morphology (Fig. 3) and chiefly consists of tube-fed pahoehoe flows, ranging in size from small pahoehoe toes to broad sheet lobes. Two of the distinguishing

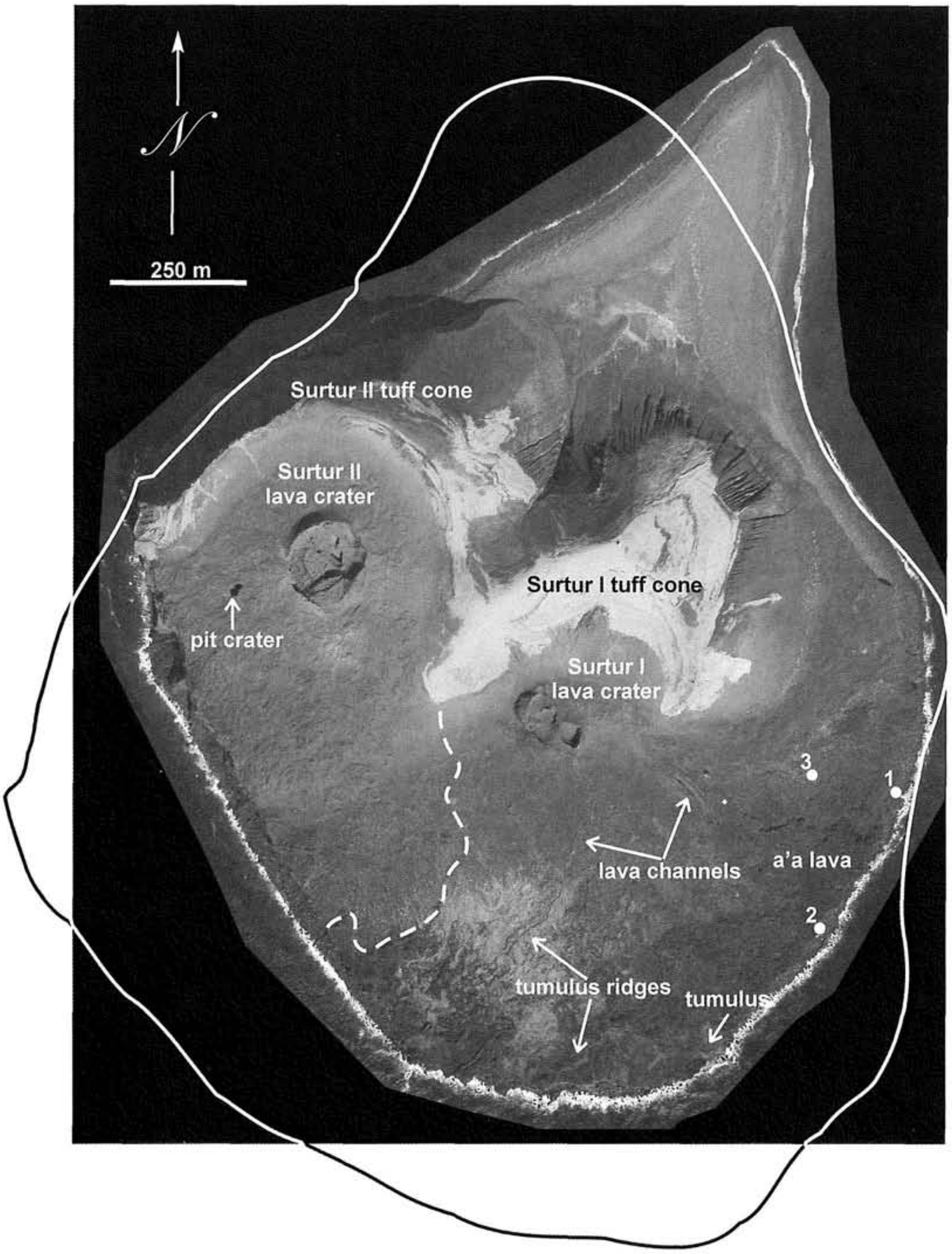

Figure 4. Recent (August 1998) aerial photograph of Surtsey with annotations referring to lava structures and localities referred to in the text. Broken line shows the western margins of the Surtur I lava shield. Also shown is the outline (black and white line) of Surtsey in July 1967. Courtesy of the National Land Survey of Iceland.

structures in this sector of the lava field are tumuli and tumuli ridges (Fig. 5c). Tumuli are isolated cupola-shaped mounds that protrude from the lava surface and typically are 1.5-3 m high (maximum 8 m) and 5-15 m in diameter (maximum 70 m). They consist of tilted crustal slabs that are split by inflation clefts and are genetically linked to lava tubes (see below). Tumuli ridges are similar structures except they have an elongate form and are as long as 350 m (Fig. 5d). Although many tumuli structures are well-exposed, others are completely coated with small surface breakouts, such that they sometimes look like heaps of entrail pahoehoe (Fig.

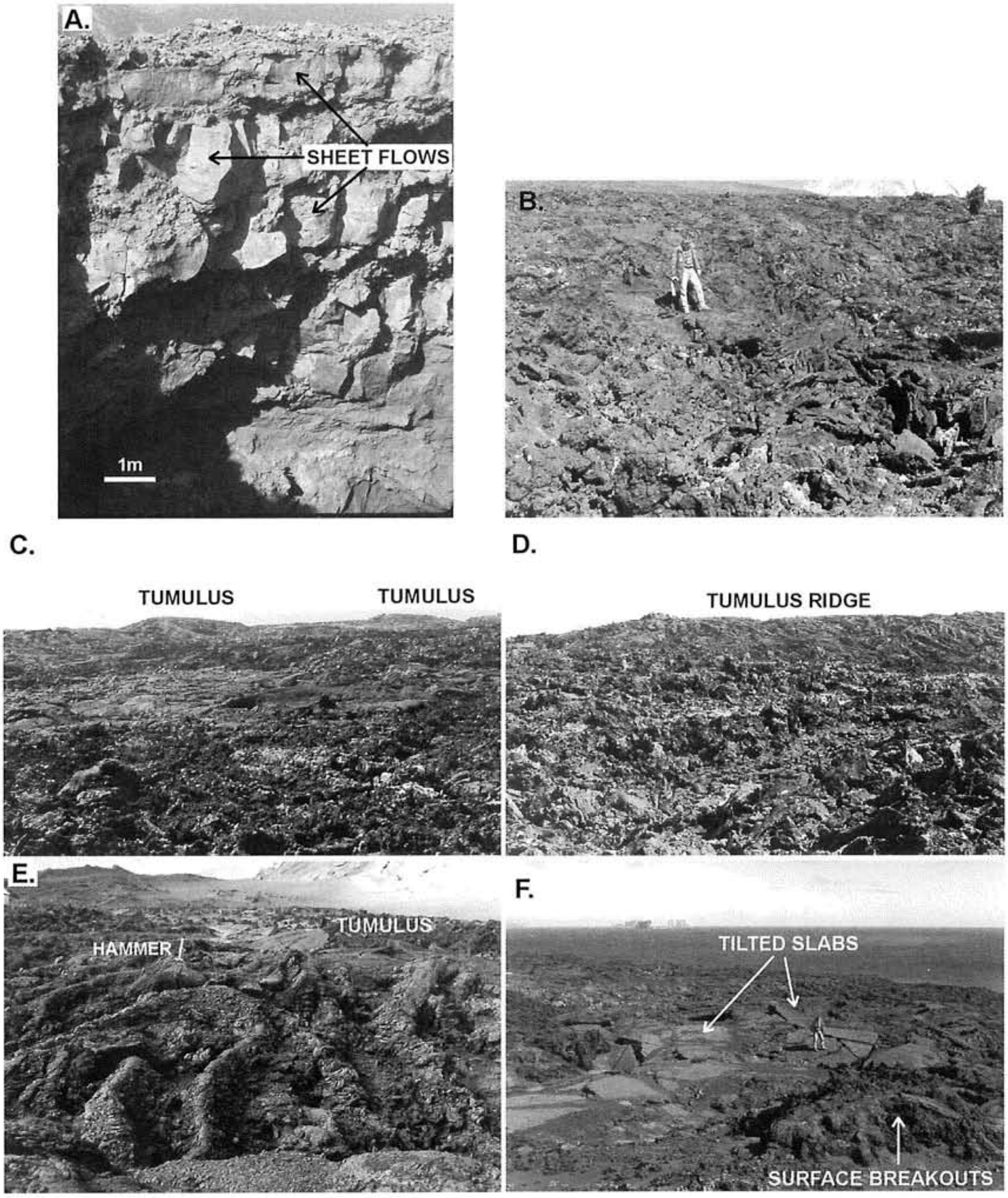

Figure 5. Photographs of lava flows and their surface structures at Surtsey. (A) Lavas in wall of pit crater. Scale bar is ~1 m. (B) Surface of slabby pahoehoe lava on the lowers slopes of the lava cone of the Surtur I lava shield. Person for scale. (C) Tumuli in Surtur I lava apron. Largest tumulus is ~5 m high. (D) A ~3 m high tumulus ridge within the Surtur I lavas almost completely disguised by small surface breakouts. (E) A pile of small flow lobes resembling heaps of entrail pahoehoe, but where formed as surface breakouts from the tumulus in the upper right corner of the photograph. Hammer is 35 cm long. (F) Large slightly tilted crustal slabs on the surface of a sheet lobe. Person for scale.

5e, Macdonald 1967). These surface breakouts are one of the characteristic features of the Surtsey lava flow field and typically occur as a stack of small lava lobes (≤1 m wide and 0.2 - 0.5 m high) that are superimposed on the original sheet lobe or tumulus surface. In places they completely disguise the original surface morphology of the flow. Field evidence show that these surface breakouts emerged through cracks in the lava surface or through skylights above lava tubes. Surfaces of broad sheet lobes are partly exposed in places as large but variably tilted crustal slabs (Fig. 5f).

Many of the tumuli that were inspected are

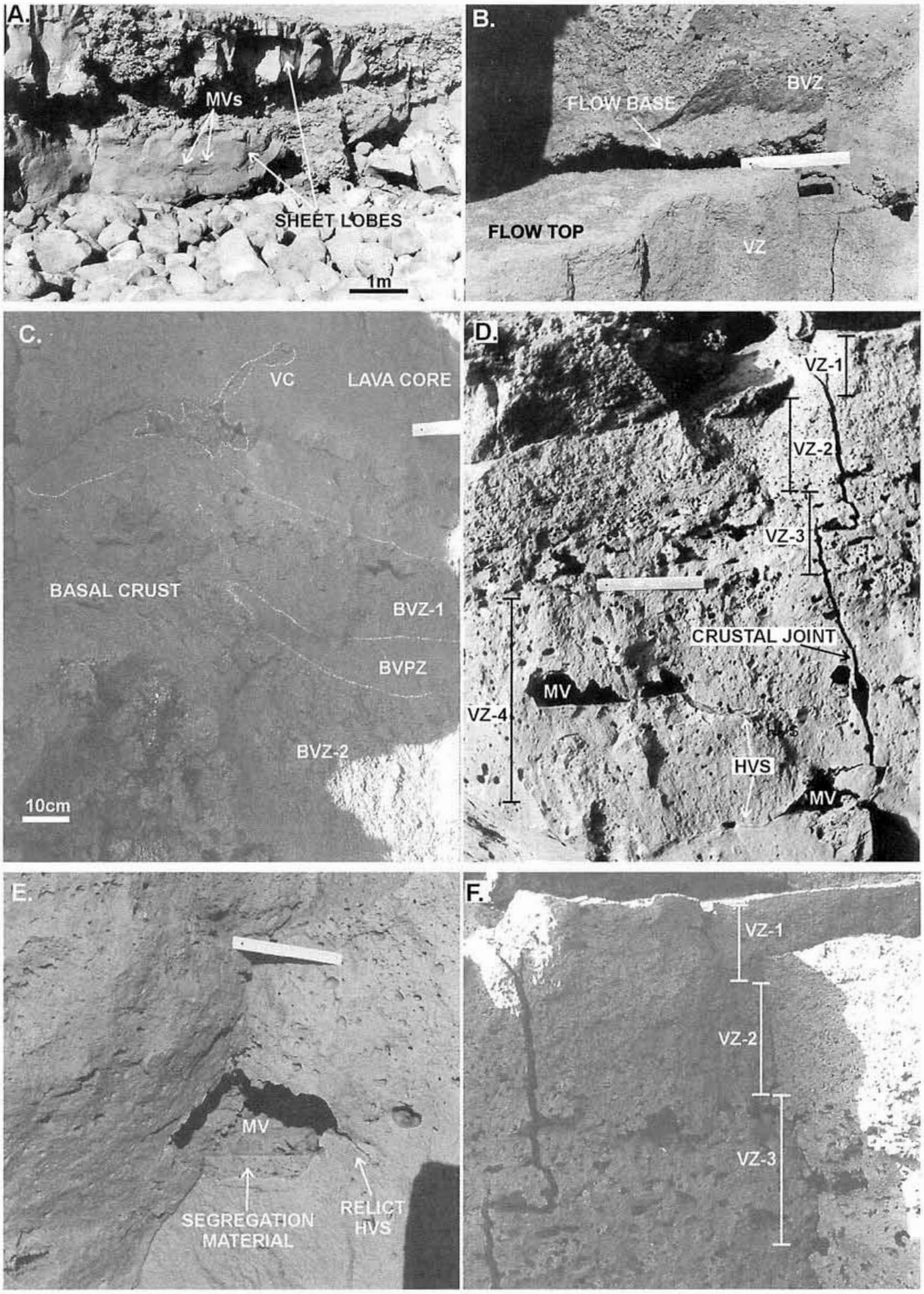

Figure 6. Photographs showing relevant examples of internal structures in a sheet lobe. (A) Terminus of two sheet lobes in the Surtur I lava shield in the cliffs at the eastern shores of Surtsey. The lower lobe features megavesicles (MVs). (B) Typical basal and upper lava surfaces on sheet lobes. Ruler is 20 cm long. (C) Close-up view of the basal crust and a vesicle cylinder extending from the basal crust up into the lava core. (D) Vesicular lava crust of a sheet lobe underlain by megavesicles and associated horizontal vesicle sheets. From sheet lobe at locality 1 (see also Figs 5 and 7 and Table 2). Ruler is 20 cm long. (E) A megavesicle, close-up view showing its characteristic dome-shaped geometry and vesicular segregated material at its base. Ruler is 20 cm long. (F) Close-up of the vesicular lava crust, showing the top three vesicular zones of the sheet lobe at locality 1 (see also Figures 5 and 7 and Table 2). Scale bar is 10 cm. Abbreviations are BVZ, basal vesicular zone, VZ, vesicular zone, BVPZ, vesicle poor zone in the basal crust, VC, vesicle cylinder, MV, megavesicle, HVS, horizontal vesicle sheet.

Table 2. Detailed log from a vertical section measured through the second sheet lobe from the top of the cliff face at the eastern shores of Surtsey (Locality 1 on Fig. 4). The sheet lobe belongs to the Surtur I lava succession. Graphic log is illustrated on Fig. 7. Abbreviations are as follows: VZ, vesicular zone; VPZ, vesicle-poor zone, VC, vesicle cylinder; MV-HVS, horizon of megavesicles (MV) and horizontal vesicle sheets (HVS).

Structural component	Thickness	Internal structures	Description
Flow top	40-70 cm		Purple to red oxidised flow-top rubble of pahoehoe slabs and clinker, intercalated with small (≤0.5 m) flow lobes produced by surface breakouts. Smooth and coherent pahoehoe surface is exposed nearby.
Lava crust	100 cm		Vesicular upper crust consisting of hypohyaline to hypocrystalline lava with downward increase in crystallinity. Joints are irregular with typical spacing of 0.4-0.7 m. When the original pahoehoe surface is preserved it features distinct flow top jointing where 20-30 cm long regular joints are spaced at 10-20 cm. The lava crust features distinct vesicle zonation, which is as follows:
		VZ-1 15-20 cm	Bluish purple to rusty red oxidised vesicular zone with average vesicularity of 30-35 vol.% and featuring 0.2 cm vesicles at the top increasing to ≤3.0 cm at the base. In top 5-7 cm, the vesicle size is 0.2-0.4 cm. Vesicle outlines are spherical. In the next 7-10 cm, the average vesicle size is 0.5-1.0 cm. Vesicle outlines are irregular and slightly elongated. In the lowest 3 cm the vesicle size ranges from 0.5 cm to 3.0 cm. Vesicles are normally elongated with irregular and convoluted outlines and show evidence of having grown by coalescence of smaller bubbles.
		VZ-2 20 cm	Vesicularity 30-35 vol.% with 0.2 cm spherical vesicles at the top increasing to 0.5-1.0 cm spherical or slightly elongate vesicles at the base. These vesicles have convoluted outlines reflecting growth by coalescence of smaller bubbles. Indistinct centimetre-thick banding is seen in places in the vesicle fabric.
		VZ-3 15-20 cm	A distinct horizon featuring 5-12 cm long and 1-5 cm high elongate segregation vesicles and scattered 1-2 cm spherical vesicles. The base of larger vesicles is flat due to accumulation of segregated material. Vesicularity is ~25 vol.%.
		VZ-4 40-50 cm	Vesicularity 5-20 vol.% with decreasing vesicle abundance from top to bottom. It features 1-6 cm spherical vesicles and a gradual downward increase in vesicle size. This vesicle zone partly overlaps the megavesicle horizon below.
Lava core	205 cm		Poorly vesicular holocrystalline lava exhibiting the following features:
		MV-HVS 40-50 cm	A distinctive horizon of megavesicles and horizontal vesicle sheets. The MVs are 10-50 cm long and 7-28 cm high. Although the MVs have somewhat irregular and convoluted outlines, they generally feature arched roofs coated by 0.5 cm thick smooth-surfaced glassy skin. The MVs have flat floors and a 3-8 cm thick bottom fill of vesicular segregated material that often connects laterally to 1-2 cm thick discontinuous horizontal vesicle sheets. Overall vesicularity is ~15-20 vol.%
		Lava with VC 170 cm	Poorly vesicular holocrystalline lava with irregular and crooked 1-4 cm wide vesicle cylinders. Each cylinder can be followed vertically for 10-15 cm, and the outcrop pattern shows that some extend up into the megavesicle horizon. One 20 cm long and 2-4 cm wide vesicle cylinder was found to terminate within the lava core. It had risen from amoeboid-shaped blob of vesicular material that extended from the basal vesicular zone. Boulders of poorly vesicular holocrystalline lava on the shore in front of the cliff feature well-developed vesicle cylinders up to 10 cm in diameter, and some were found to connect to 2-4 cm thick horizontal sheets.
Basal crust	55 cm		Hypohyaline to holocrystalline lava with the following vesicle zonation:
		BVZ-1 10 cm	Vesicularity 5-10 vol.% with 0.2 cm spherical vesicles at the base and ≤11 cm elongate segregation vesicles at the top.
		BVPZ 10-15 cm	Non-vesicular lava.
		BVZ-2 20-40 cm	Vesicularity ~25-30 vol.% with 0.5-2 cm spherical and elongate (stretched) vesicles at the top, decreasing to 0.1-0.2 cm spherical vesicle at the base
Basal surface			Convoluted base with spinous basal surface and discontinuous horizons of centimetre-large clinker.

hollow inside, featuring a large chamber roofed by relatively thin crust. The surface of these tumuli are usually covered by numerous surface breakouts illustrating that at some stage their chamber was full to the brim with lava. Inspection of their interiors shows that individual

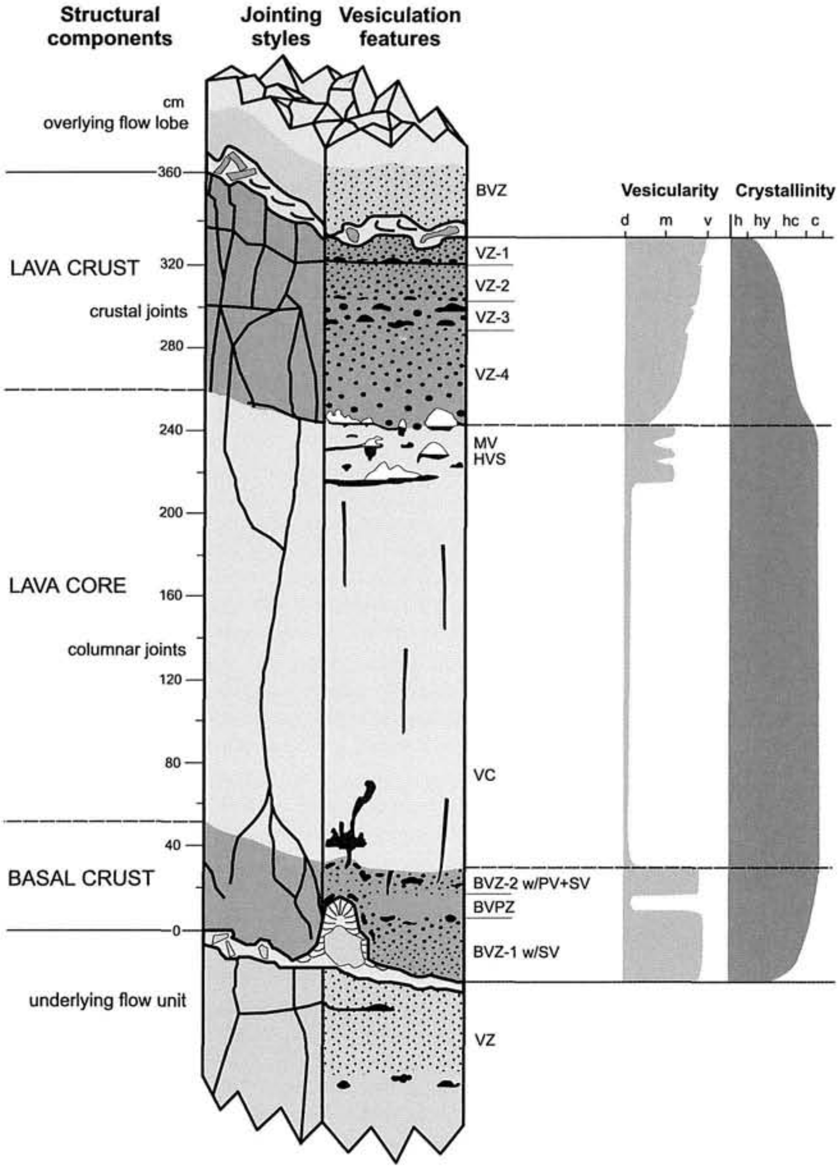

Figure 7. Representative graphic log showing vertical distribution of internal structures in a sheet lobe within the Surtur I lava flow (Locality 2 in Fig. 4). The main structural components; the lava crust, lava core, and basal crust are shown on the left. The left column illustrates the jointing of the lava, thin lines indicate crustal joints and thick line denote columnar joints (Thordarson and Self, 1998). The right column shows vesiculation features. Abbreviations are as follows: VZ, vesicular zone; MV, megavesicle; HVS, horizontal vesicle sheet; VC, vesicle cylinder BVZ, basal vesicular zone; SV+PV, segregation and pipe vesicles. Also shown are profiles depicting vertical changes in vesicularity and crystallinity as determined by visual estimates in the field aided by microscopic examination of a representative suite of hand samples and thin sections. Vesicularity scale is modal percent and intervals of crystallinity are h, hyaline (0-10% crystals); hy, hypohyaline (10-40% crystals); hc, hypocrystalline (50-90% crystals); and c, holocrystalline (90-100% crystals).

tumulus chamber connects to lava tubes on the upflow and the downflow side. At locality 3 in Fig. 4 the tumulus roof is partly collapsed and allowed for easy access to the chamber. This tumulus chamber is 5-8 m wide and ~10 m long. Originally it must have been 3-4 m deep with its roof standing at least 2 m above surrounding lava surface although the original tumulus geometry is now somewhat obscured by numerous surface breakouts that cover the outer slopes (Fig. 5e). The chamber has one 2 m high and 4 m wide tube entry on the upflow side, but three 1-3 m wide tube exits on the downflow side. These observations show that the tumulus formed by inflation of the crust over a rather broad pool of molten lava that was fed by a relatively large lava tube. Tumuli with partly collapsed roofs and empty tumulus pools are scat-

Table 3. Detailed log from a vertical section measured through a tumulus in the third sheet lobe from the top of the cliff face at the southeastern shores of Surtsey (Locality 2 in Fig. 4). The lobe most likely belongs to the Surtur I lava succession. Graphic log is illustrated on Fig. 8 and a sketch of the tumulus is shown in Fig. 9. Abbreviations are as in Table 2.

Structural component	Thickness	Internal structures	Description
Lava crust (tube roof)	55 cm	VZ-A 30-40 cm	Vesicularity is ~20 vol.%. Vesicle size increases downwards, from ≤0.4 cm spherical vesicles at the top to ≤2 cm elongate stretched vesicles at the base. A gas-parting surface and a gas-blister separate zones A and B.
		VZ-B 20 cm	Vesicularity is ~15 vol.%. Vesicle size increases downwards from ≤0.4 cm spherical vesicles at the top to ≤5 cm elongate stretched vesicles at 15cm depth. Lowest 5 cm, however, contain ≤1 vol.% of small (≤1.0 cm) spherical vesicles.
			These zones connect directly with the uppermost vesicular zones in the lava on either side of the tumulus.
Hollow tube	70 cm		Void bounded by an arched roof and a flat floor.
Tube-fill	180 cm	VZ-1a 10 cm	Vesicularity ~25-30 vol.% with ~0.1 cm spherical vesicles at the top, increasing in size downwards to ~0.5 cm.
		VZ-1b 10-15 cm	Sharp transition to a horizon that is dominated by 3-7 cm long and 1-3 cm high segregation vesicles with arched roofs and a flat base
		VZ-1c 35-40 cm	Vesicularity ~25-30 vol.% with 1-2 cm spherical vesicles at the top decreasing to ≤1.0 cm vesicles at the base. Lower contact is sharp and undulating.
		VPZ-1 40 cm	Vesicularity ≤5 vol.% with a few 0.5-3 cm vesicles evenly dispersed throughout the zone. Vesicles are usually spherical, but a few are elongated (stretched) in horizontal direction.
		VZ-2 20-25 cm	Vesicularity 15-25 vol.% with ≤1 cm spherical vesicles at the top, decreasing to ≤0.5 cm vesicles near base. Upper contact is diffusive because some of the larger vesicles were buoyant enough to rise across it and into VPZ-1. Lower contact is knife sharp and the lava contains scattered ≥1cm long stretched vesicles in the 5 cm immediately above the contact. Midway through the tube-fill VZ-2 thins sharply and continues as a parting surface. Near this transition a vertical ~7 cm wide vesicular band cuts through VPZ-1, linking VZ-2 to VZ-1c, and appears to have formed by a diapiric rise of vesicular mush derived from VZ-2.
		VPZ-2 40-50 cm	Very vesicle-poor (<1 vol.%) lava, with only a few 1 cm spherical vesicles. This zone has elongate and concave upward geometry and apparently a part of the tube itself, in similar fashion as VPZ-1.
		VZ-3 10-15 cm	Vesicularity ~10-15 vol.% with ≤0.4 cm spherical vesicles at the top increasing to ≤1.0 cm vesicles of spherical or elongate (stretched) shape. In places this zone is in contact with the basal vesicular zone of the tumulus and the lava on either side.
Basal crust	30 cm	BVPZ 0-10 cm	Discontinuous, wedge shaped zone of vesicle poor lava within the basal crust of the tumulus
		BVZ 20-25 cm	Vesicularity ~25 vol.% with 2 cm spherical to irregular vesicles in the top 10 cm showing evidence of upwards migration. Next 5 cm features ≤3.0 cm long elongated (stretched) segregation vesicles, whereas lowest 5cm contain small (≤0.3 cm) spherical vesicles.

tered about in the lavas at Surtsey. On one occasion, I saw that a surface flow had reentered a tube system through such an opening, which is probably a common occurrence in this type of lava.

General characteristics of the Surtur I lava flows in a vertical succession

The eastern shores of the island feature 3-10 m high sea cliffs that provide readily accessible exposures through the lava succession of the Surtur I shield. Here, as well as elsewhere along the shores of the lava field, the cliff consists of numerous flow lobes of variable thickness and lateral extension. The thickest lobes are 2-6 m and the thinnest 0.5 m. Most of these flow lobes are pahoehoe or slabby pahoehoe. A few small a'a flow lobes are present in the succession, which is also capped by small, 1.5 to 2.0 m thick, a'a lava flow further to the south (Fig. 1). The beach in front of the cliffs is covered

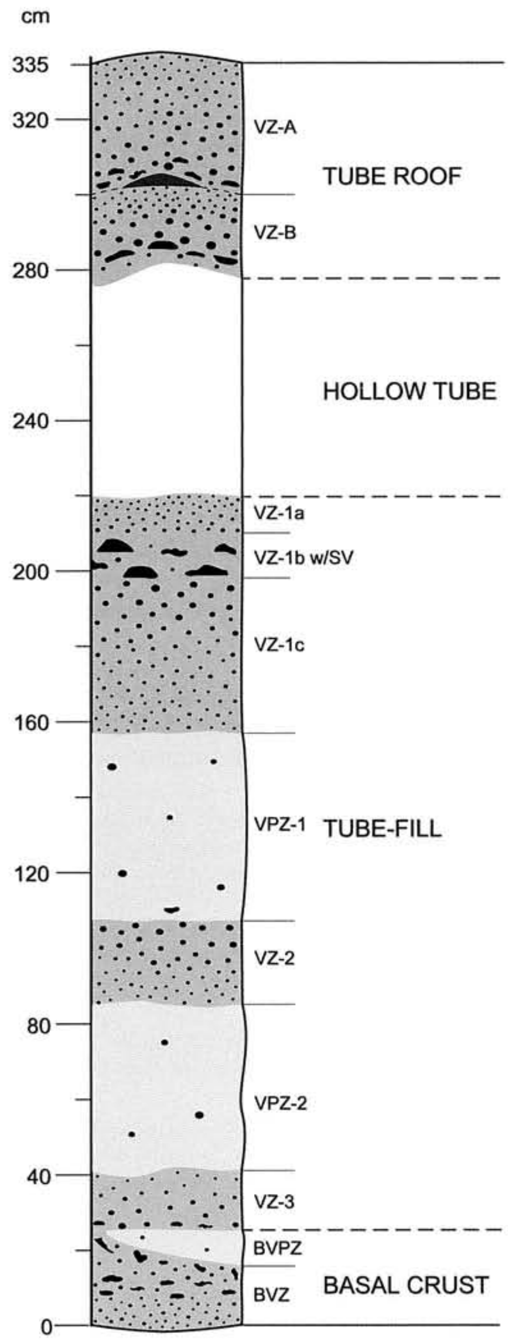

Figure 8. A graphic log illustrating the vertical arrangement of internal structures in the tumulus at locality 2 (see Fig. 4). Abbreviations as in Fig. 7.

by large (0.5 m) angular to subrounded lava boulders formed during the breakdown of the 1966-1967 lava flows by wave erosion. However, this sector of the Surtsey lavas has suffered much less erosion than other parts of the flow field, today the shoreline is just inside its original position at the end of the eruption in June 1967 (Fig. 4). The descriptions that follow are based on observations made along these cliffs, which represent the distal sector of the Surtur I lava apron.

The most prominent lava units in these cliffs are pahoehoe sheet lobes that typically are 50 m to 200 m wide (or long) and 2-4 m thick (maximum measured thickness is ~6 m). For the most part the thickness of each sheet lobe is rather uniform or between 1.5 and 2.5 m (Fig. 6a). However, the sheet lobes commonly swell above 0.5-1.0 m deep lows in the underlying lava surface to more than double the thickness of the lava on either side. In profile these local swells have shapes of a tumulus and hollow lava tubes are routinely found in their centres (see below). A 0.5-1.0 m thick stack of much smaller pahoehoe lobes, with typical dimensions between 0.2-1.0 m, often separate the sheet lobes. Lobes with slabby pahoehoe and a'a surface morphologies are also present. Discontinuous layer of flow-top rubble, up to 0.5 m thick and 20 m long, consisting of a mixture of spinous clinker and slabs of pahoehoe crust sometimes separates the sheet lobes.

Internal structures of sheet lobes

The sheet lobes exposed in the cliffs along the eastern shores have similar internal structures. They exhibit the threefold division of vesicular basal crust, crystalline lava core, and an upper vesicular lava crust that is common to this type of pahoehoe lava (e.g., Self *et al.*, 1998). The general arrangement of internal structures and textures in Surtsey sheet lobes are described below. The details of a section measured through a sheet lobe at locality 1 (Fig. 4) is given in Table 2 and illustrated in Fig. 7.

The basal surface of the sheet lobes is either convoluted and spinous or smooth and billowy pahoehoe surface with a 1-4 cm thick glassy selvage that marks the very bottom of the basal crust (Fig. 6b). The basal crust is normally <10% of the total flow thickness. It consists of hypohyaline to hypocrystalline lava featuring a distinct basal vesicular zone with vesicularity between 25-35 vol.%. Sometimes the basal crust is locally split into two by a thin horizon of vesicle-poor lava, which terminates abruptly when followed for several meters. Crystallinity and vesicle size generally increases upwards in the basal crust, and the upper part of the basal vesicular zone sometimes features irregular and elongate segregation vesicles and, more rarely, pipe vesicles. Small cylinders and amoeboid-shaped patches are often present above local irregularities in the basal lava surface, extending tens of centimetres into the overlying

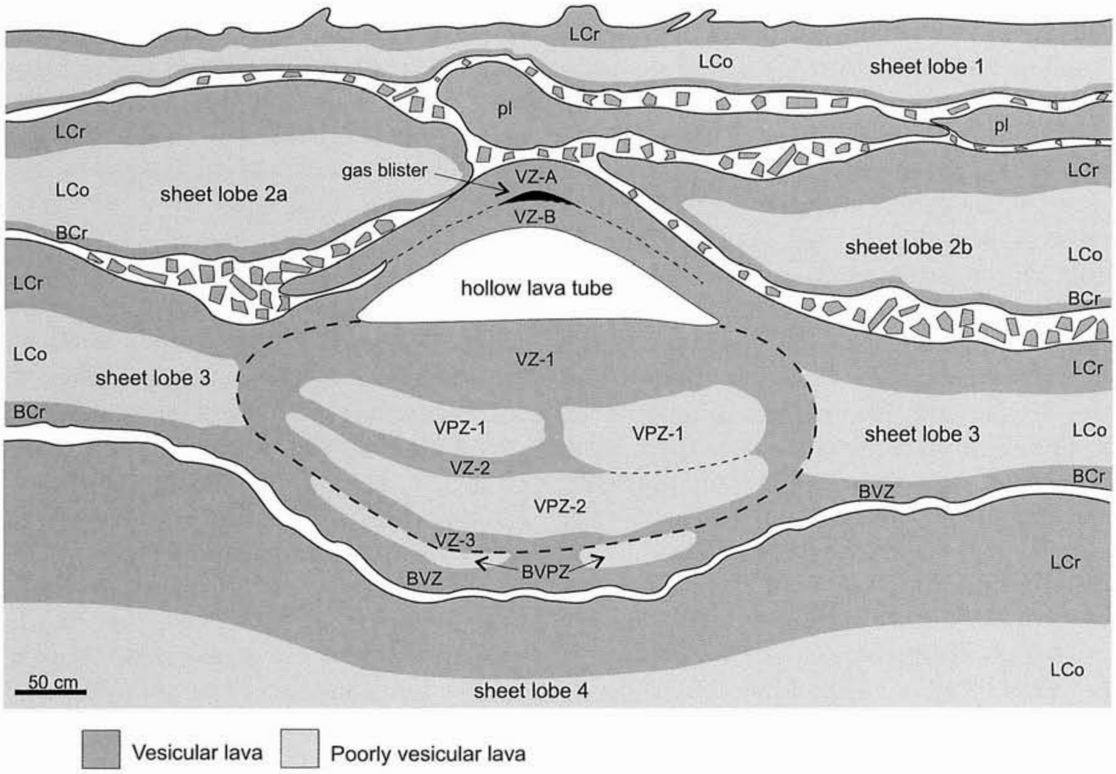

Figure 9. A field sketch of the tumulus at locality 2 (see Fig. 4) outlining its morphology and its relationship with the surrounding lava. Bold broken line outlines the tube-fill lava, whereas thin broken lines indicate parting surfaces. The threefold division lava crust (LCr), lava core (LCo), and basal crust (BCr) are indicated for the sheet lobes; pl stands for small pahoehoe lobe (surface breakout). Other abbreviations are as in Fig. 7.

lava core (Fig. 6c). These structures clearly originate within the basal vesicular zone and contain vesicular (~40 vol.%) segregated material.

The lava core is uniformly holocrystalline and is normally the thickest component of each flow unit or between 50% and 55% of the total thickness (Fig. 7). Joints are irregular and typically spaced at 0.5-1.0 m. The lava core contains 2 vol.% of centimeter-sized spherical vesicles and features scattered 0.5-4.0 cm wide vesicle cylinders that can be followed vertically for 10-15 cm. Outcrop patterns indicate that originally most of these cylinders extended all the way through the lava core, although some clearly terminate within the lava core (e.g. Fig. 6c). Vesicle cylinders were never found within the upper lava crust. In many sheet lobes a distinct horizon of megavesicles (i.e., large segregation vesicles) occurs at the top of the lava core, immediately below the vesicular lava crust. At locality 1 these megavesicles are 8-50 cm long and 9-20 cm high with irregular outlines, flat floors, and arched roofs (Fig. 6d). At the bottom of each megavesicle is a 2-9 cm thick accumulation of segregated material with 3-15 vol.% vesicularity (Fig. 6e). Horizontal vesicle sheets, 1-3 cm thick, are frequently found in direct continuation of the segregated material in the megavesicles. Field relations imply that the megavesicles are formed by localised gas accumulation within the horizontal vesicle sheets that develops into a giant gas bubble rising from the upper surfaces of the sheets into the viscous lava above.

Closely spaced (0.3-0.7 m), highly irregular joints and a progressive upward decrease in crystallinity characterise the vesicular lava crust, which makes up between 35% and 40% of the total flow thickness (Fig. 7). Approximately two out of every three crustal joints terminate abruptly at the lava core/lava crust boundary, whereas the reminder merges with the joints of the lava core. The lava crust usually features several vesicular zones, each with 20-35 vol.% vesicularity and a downward increasing vesicle size (Figs 6f and 7). The sheet lobes are either capped by smooth pahoehoe flow surfaces (Fig. 6b), thin rubble of pahoehoe slabs and clinker, and/or small lava lobes (surface breakouts).

Internal structures of a tumulus

The descriptions presented below are based on a detailed vertical section measured through a tumulus within a sheet lobe in the lava cliffs along the southeastern shores of Surtsey (Locality 2 in Fig. 4). Section measurements and descriptions are presented in Table 3 and illustrated by the graphic log in Fig. 8. The tumulus geometry and arrangement of internal structures are shown in Fig. 9. The tumulus is ~3.5 m high and 5 m wide and laterally it connects with an ~2.0 m thick pahoehoe sheet lobe that can be followed in the cliffs for several hundreds of meters. The tumulus is located where there is an ~1 m deep and ~5 m wide low in the underlying lava flow, suggesting that the tumulus formation may have been initiated by irregularities in the subsurface. The lowest 2.1 m of the tumuli are composed of solid lava overlaid by a 0.7 m high and 3 m wide cupola-shaped lava tube (Figs. 8 and 9). The tube is capped by 0.6 m thick arched roof that is partly covered by small surface breakouts and flow top rubble. The tube roof contains two vesicular zones, which when followed sideways merge with the vesicular lava crust in the sheet lobe on the either side of the tumulus. The upper vesicular zone (VZ-A) connects the topmost vesicular zone of the sheet lobe, whereas the lower zone (VZ-B) merges with the underlying one. Below the hollow tube is flat-topped lava representing the tube-fill, which is ~1.8 m thick, implying that at time of solidification the tube was about two-thirds full of lava. The tube-fill features a complex zonation of strongly vesicular and poorly vesicular lava and contains higher number zones than the lava on both sides (Figs 8 and 9). Vesicular zones VZ-1 and VZ-2 and vesicle poor zones VPZ-1 and VPZ-2 are exclusively confined to the tumulus. The lowest vesicular zone (VZ-3), however, merges with the basal vesicular zone that underlies the tube-fill and continues laterally along the base of the sheet lobe on either side of the tumulus (Fig. 9). The continuity of the basal vesicular zone and the vesicle zones in the tube roof show that the tumulus is an integral part of the sheet lobe. The internal structures of the tube-fill, however, demonstrate that it represents a separate lava batch emplaced later than the main body of the sheet lobe. The surface breakouts that cover the tumulus confirm that at some stage the tube was completely full of lava, in fact so full that it inflated to form the arched tumulus roof. About 5 m to the west is another smaller tumulus in the same sheet lobe, and it displays similar internal arrangement of structures as the one described above. However, it does not feature a hollow tube and most likely represents a confined internal lava pathway or lava tube that was not drained of its lava before solidification.

DISCUSSION

Contemporary descriptions (*e.g.,* Thórarinsson 1965, 1966, 1967a, 1967b, 1968, Einarsson 1965) of the effusive activity clearly show that the construction of the Surtsey shields involved two distinct lava transport and emplacement mechanisms, exemplified by surface flows on one hand and tube-fed flows on the other. As is commonly the case in natural systems these mechanisms represent two end members in a continuous spectrum of processes that in detail are more complex. However, these flow types are useful descriptors of these mechanisms because they encompass the principal processes involved in construction of the Surtsey lava shields. As will be shown these mechanisms produce distinct lava types that can be related to specific eruption processes, which are responsible for the construction of the two principal structural units of the Surtsey lava shields, the lava cone and the flanking lava apron (Figs 1 and 3).

The Surtur I and II lava cones are capped by lava craters, which at the time of the eruption were occupied by small lava ponds. In the vicinity of the lava craters the surface lavas are typically cavernous shelly pahoehoe and, to a lesser extent, sheet flows. The outer slopes of the lava cones are typically covered by slabby pahoehoe flows, although it also features levee-bounded lava channels and subsidiary channel overflows. However, the dominance of sheet flows in the pit crater exposure suggests that this lava type is more common in this sector of the shields than indicated by the surface exposures. The overall morphology and structure of the lava cone flows at Surtsey show a striking resemblance to the fountain-fed and overbank surface flows produced by the summit lava pond at Mauna Ulu (e.g., Swanson 1973) and descriptions of lava effusion at Surtsey show that they were formed in a similar manner (see below).

Contemporary descriptions show that surface flows were the dominant type of lava extrusion in the early stages of each effusive phase (Table 1), when the activity was characterised by periodic rise and drop of lava in the craters and episodic lava fountaining. The short periodicity of these episodes suggests that they were driven by pulsating degassing of the magma during its rise to the surface rather than variations in magma discharge. Some surface flows were fed directly from lava fountains (i.e., fountain-fed flows), whereas others were formed as the gas-inflated lava pond rose to its brim and spilled lava over the crater rims (i.e., overbank flows). Flowing away from the crater as broad sheets or wide and braided lava tongues they often advanced at relatively high velocities (10-20 m/s) and commonly featured spectacular red-glowing surfaces. Such flows are characterised by high cooling rates and rapid changes in lava rheology during emplacement, imposing stringent conditions on how far they can flow (e.g., Keszthelyi & Self 1998). Although a number of surface flows reached the sea, they typically advanced a short distance from the lava craters and were the essential agents that built up the lava cones. This is confirmed by data on the summit elevation of the cones, which show that they grew most rapidly in the early stages of each effusive phase when surface flow activity was most vigorous. Later, when lava transport was essentially confined to tubes and surface flows were rare, the growth of the lava cones was virtually reduced to a standstill (Thórarinsson 1966, 1967a, 1967c, 1968).

The gently sloping lava aprons at Surtsey feature distinct hummocky topography where tumuli, tumulus ridges and small lobes formed by surface breakouts are the distinguishing surface structures. Vertical sections, however, show that the apron chiefly consists of compound pahoehoe. Furthermore it shows that tube-fed sheet lobes and, to a lesser degree, stacks of small pahoehoe lobes are the characteristic lava types. The overall morphology and structure of the Surtsey lava aprons show strong resemblance to that of inflated pahoehoe flows, which make up the distal sectors of tube-fed lava fields in Hawaii (e.g., Mattox *et al.* 1993) and on Icelandic shield volcanoes (Rossi 1996, 1997, and unpublished observations by the author). Contemporary observations show that tube-fed lavas were the main contributors to the construction of the lava apron (Table 1) and were largely responsible for the lateral growth of the Surtsey lava shields. It is therefore appropriate to examine in more detail the chief components of the lava apron and their importance for assessing the lava emplacement mechanism.

The sheet lobes at Surtsey have strikingly similar internal structures to that of inflated sheet lobes from the currently active Pu'u O'o-Kupaianaha pahoehoe lava flow field in Hawaii, as well as to structures of sheet lobes from other inflated pahoehoe lava flows around the world (e.g., Fig. 20 in Thordarson & Self 1998). The three-part structural division of the sheet lobes into basal crust, lava core, and lava crust are equivalent to the bottom crust, molten lava core, and upper crust of actively inflating lobes (Hon *et al.* 1994, Thordarson 1995). These divisions provide the keys for understanding the emplacement mechanism of the Surtsey sheet lobes.

Studies of segregation structures in basaltic lavas (e.g., Goff 1977, 1996, Thordarson 1995, Thordarson & Self 1998) have shown that the segregation principally occurs at the lower solidification front (i.e., basal crust to lava core boundary) and that it is an integral part of the lava emplacement process. As the flow of lava is coming to halt and immediately thereafter, the buoyant segregation melt rises as vertical vesicle cylinders through the molten lava core. When the cylinders meet the upper solidification boundary (i.e., lava core to lava crust boundary) they spread out as horizontal vesicle sheets. Megavesicles form at the upper surfaces of the sheets as a consequence of gas accumulation initiated by local instabilities or irregularities within the sheets. They acquire their dome and flat-based shapes because they rose into the lowest, and then viscous, part of the lava crust (Thordarson & Self 1998). The outcrop pattern of segregation structures in sheet lobes at Surtsey is consistent with this representation (e.g., Fig., 7). The estimated rise velocity for the segregation melt in a typical cylinder of basalt lava is of the order of 3.5×10^{-3} cm/s (~3 m per day). Accordingly, at that speed it would have taken just over a day (<29 hr) for the vesicle cylinders to rise to the top of the lobe. However, the transformation from vesicle cylinders to horizontal vesicle sheets and megavesicles in the Surtsey sheet lobe occurs well within the lobe or at normalised height $h/l = 0.47–0.58$ (h = height to sheets and megavesicles in lava; l = total thickness of lobe). This illustrates that the solidification front was positioned at ~1 m depth when the vesicle cylinders were transformed into horizontal vesicle sheets. Thus, it would have taken about half to three-quarters of a day (12-18 hrs) for the cylinders to rise this far. If the Surtsey sheet lobe at locality 1 was entirely molten when they came to rest, then the law of conductive cooling predicts that the depth to the solidification front after 1 day would be at 0.4 m (e.g., Hon *et al.* 1994). Also it would take ~7 days (range 5.6-8.3 days) for it to reach the depth of ~1 m. There is a clear contradiction here and the logical conclusion is that a surface crust of considerable thickness was formed during the emplacement of the sheet lobe. This is an important conclusion because formation of such crust is one of the trademarks of lava inflation and endogenous growth (e.g. Hon *et al.* 1994, Thordarson 1995, Kauahikaua *et al.* 1998 Self *et al.* 1998,).

The general increase in vesicle size with depth in the lava crust is consistent with the conclusion that the crust grew in thickness during lava emplacement. If the lobe was wholly molten when it came to rest, the largest vesicles should be concentrated towards the top of the crust and the smaller ones at the base because larger vesicles rise faster than smaller ones (Vergniolle & Jaupart 1986). The fact that a reverse trend is observed is concordant with incremental growth of the lava crust during emplacement, because as the crust thickens the cooling rate decreases and, consequently, the bubbles that are trapped lower in the crust have progressively more time to grow (Cashman & Kauahikaua 1997). The same results are obtained from evaluations of the two-tiered jointing pattern, crustal joints of the lava crust versus columnar joints of the lava core (Fig. 7). The highly irregular crustal joints are formed by jostling of the lava crust during lava inflation, whereas columnar joints form under a more relaxed stress field in a stagnant lava body (Thordarson & Self 1998).

The distribution of internal structures of Surtsey sheet lobes are best explained in terms of endogenous emplacement, characterised by steady injection of lava into a molten core surrounded by insulating crust and wholesale inflation of the upper lobe surfaces (e.g. Hon *et al.* 1994, Thordarson & Self 1998).

Tumuli and tumulus ridges are one of the most distinguishing lava inflation structures at Surtsey. They are surface manifestation of lava tubes or preferred internal lava pathways. However, their relationship to inflating sheet lobes may not be instinctively obvious and thus are examined here in more detail. The basal and top vesicular zones in the tumulus at locality 2 clearly show it is an integral part of the sheet lobe, whereas the internal structures of the tube-fill indicate that it evolved separately from the main lava body at a later stage in the emplacement. Not only did lava continue to flow through the tube after flow had ceased within the main body of the sheet lobe, but the roof above the tube continued to inflate as is evident by its arched geometry.

Observations in Hawaii show that lava tubes and tumuli structures can form during later stages of sheet lobe emplacement because of the localisation of flow along preferred internal pathways and continued inflation above active tubes (e.g., Mattox *et al.* 1993, Peterson *et al.* 1994, Kauahikaua *et al.* 1998). Consequently, the formation of tumuli (or tumulus ridges) and associated lava tubes, such as the one described previously, can be viewed as follows. Initially the sheet lobe is emplaced as an inflating sheet driven by steady transport of lava through a molten core surrounded by insulating crust. At that stage the upper surface of the sheet lobe is essentially horizontal, whereas its basal surface generally follows the irregularities in the underlying surface. Thus, from the start, the lava flux through the molten core is somewhat greater above lows than above highs. With continued inflation of the sheet lobe, the flow of lava gradually becomes more and more redirected towards regions of higher flux. Eventually, thinner regions of the sheet lobe stagnate, and flow of lava is entirely restricted to a few preferred pathways or lava tubes that feed lava to the steadily advancing flow front where new lobes are formed. Inflation of the tube roof continues as long as the tube is full with lava and the flow maintains excess hydrostatic pressure. Hollow tubes are formed when the supply of lava is reduced or terminated and the slope is enough to promote drainage of the internal lava pathway. At Surtsey slopes as small as 1-2° appear to be sufficient to promote such draining from the tubes.

The formation of cupola-shaped tumuli and tumulus ridges are easily explained by the mechanism described above. The tumuli are formed by localised inflation of the lava crust above small pools in the internal lava rivers, whereas the tumulus ridges are formed by inflation above relatively straight sections of preferred internal lava pathways or tubes. The fact that the tumulus chamber at locality 3 has more than one tube exit suggests that the lava pools may sometime initiate bifurcation within the lava tube system.

In summary, the observations presented here show that the Surtsey lava flow field consists of two small lava shields produced by two prolonged effusive eruption phases. Each shield features two principal structural units, the lava cone and the outer lava apron. The lava cones were constructed in the early stages of each effusive phase by surface flows that emanated from small lava ponds contained within the summit lava craters. This activity produced shelly pahoehoe and sheet flows. The lava apron was constructed in the later stages of each phase when the level of the lava ponds had dropped well below the rims of the summit lava craters and the flow of lava to the active flow fronts was essentially confined to internal pathways or lava tubes. As the lava emerged from the tubes it spread to form either a series of small budding lava lobes or broad but thin (tens of centimetres thick) sheet lobes. As the sheet lobes spread and inflated, they attained lateral dimensions of tens to hundreds of meters and thicknesses of several meters. The existing tube system was extended by flux-induced localisation of flow within the sheet lobes, which carried the lava further to produce more lobes in front of new tube exits and thus gradually enlarging the lava apron. Lava emerging from tubes near or at the shorelines was the chief agent in extending the lateral dimensions of the lava aprons, whereas lava breaking out from tubes farther up in the lava field piled on top of existing lobes and added to their vertical dimensions.

CONCLUSIONS

The Surtsey lava shields consist of two principal structural units, the lava cone and the flanking lava apron. These structural units were formed by discrete lava emplacement mechanisms and consist of distinct lava types and facies associations. Despite their mild alkalic affinity, the Surtsey lava shields have morphologies that are strikingly similar to that of tholeiitic monogenetic pahoehoe lava shields in Iceland. This similarity in geometry and morphology implies that the effusive activity at Surtsey and the lava types it produced can be used as an analogue to establish a conceptual model shield volcanoes, their eruption mechanism and their mode of construction. This could be accomplished by:

(a) more comprehensive study of lava morphologies, types, and facies associations at Surtsey than presented in this report,
(b) systematic analysis of the effusive activity as revealed by contemporary descriptions and other documents (i.e., photographs and films), and
(c) all-encompassing study comparing the Surtsey lava shields to other Holocene lava shields in Iceland.

Such a study is highly desirable because it will enlighten us about the processes involved in construction of shield volcanoes and provide us with a valuable tool to recognise and map various components of shield volcanoes in older volcanic succession.

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